

Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers under Very High Wind Conditions

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LONG-TERM GOALS

The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.

OBJECTIVES

This project seeks to improve the accuracy of air-sea interfacial flux parameterizations in coupled sea state/marine weather forecasting models, with a particular focus on refining and incorporating the role of wave breaking and sea spray in severe conditions. The approach adopted is to develop more realistic parameterizations for breaking occurrence and strength, and sea spray/spume source functions and validating them in test-bed models against observations. The end goal is to implement these improvements in a coupled COAMPS/WaveWatch III model for operational use.

APPROACH

Our approach is to build substantially on our accumulated expertise in sea surface processes and air-sea interaction (Banner) and numerical weather modelling (Leslie, Morison) to identify and close fundamental knowledge gaps in order to improve the modeling accuracy for severe marine meteorological events such as hurricanes. Such improvements depend critically on gaining a more complete understanding of severe sea state phenomena linked to wave breaking, due to their increased surface drag and allied air-sea flux enhancements, including sea spray production.

Quantifying the distribution of wave breaking events has progressed substantially within this project as a result of an intensive collaboration on breaking wave observations with D. Farmer and J. Gemmrich (IOS, Canada) in FY01, and more recently with J. Gemmrich (UVic, Canada). From their IOS storm wave datasets, a robust *threshold behavior* was identified for wave breaking at different scales in terms of the wave spectral saturation level $\sigma(f)$ (Banner et al, 2002, hereafter BGF02). The saturation $\sigma(f)$ is

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14. ABSTRACT The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.					
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given by $\sigma(f) = (2\pi)^4 f^5 F(f) / 2g^2$, where $F(f)$ is the wave energy spectrum and f is the frequency. This result has proven very useful in our ongoing effort to parameterize wave breaking spectrally in wind-wave models, and underpins our new spectral source term formulations for the wave energy dissipation rate. It is also being used in the spray/spume production term formulated in collaboration with C. Fairall (NOAA). More recently, Gemmrich (2005) has analyzed the evolving wave breaking properties of a developing strong wind sea event during the recent ONR-funded FAIRS experiment conducted in October 2000 from RV FLIP (please see <http://airs.apl.washington.edu/projects/fairs/summary.html>).

Model development in this project has focused on refining *full-bandwidth* computations of the directional wave spectrum and its tail region using an ‘exact’ version of the nonlinear wave-wave interaction source term in the radiative transfer equation for the wave field. We have concentrated on fetch-limited and duration-limited growth cases, since the bulk of observational data exists for these cases. This ensures that modeled spectral saturation levels (and dissipation rates) are consistent with observed levels, and allows predicting spectral breaking wave properties and hence enhanced air-sea fluxes associated with wave breaking. This information is needed to underpin future operational versions of coupled atmosphere-wave-ocean models.

We have focused strongly on formulating, implementing and refining modeling strategies for: (a) extracting the relevant wave breaking parameters and (b) calculating wind stress/roughness length enhancements and updating the surface layer winds accordingly. For (a), we have significantly refined our previously reported capabilities for calculating the spectral density of mean breaking wave crest length/unit area. This is a primary goal of this project, as this quantity is central to the prediction of breaking wave enhancements to the wind stress, and development of a spray/spume source function based on sea state rather than the wind strength. To this end, further progress has been made in refining the form of S_{ds} proposed by Alves and Banner (2002) [hereafter AB02] and on advances in predicting wave breaking probabilities at different wave scales in BGF02. In particular, the AB02 form of S_{ds} was upgraded to incorporate the observed BGF02 breaking saturation threshold. Also, various refinements were introduced to its spectral distribution. This was done in order to provide a much better match to the wind input source function S_{in} at higher wavenumbers, and to recently published observations of the spectral density of breaking wave crest length/unit area. To progress, we have had to invest very considerable effort evaluating various versions of the wind input source terms S_{in} , and propagation schemes in the radiative transfer evolution equation, in order to ensure accuracy and minimise computational instabilities that can develop at higher wavenumbers.

In FY06, we investigated forecasting breaking wave properties at the spectral peak, and looked very carefully at the newly available data from the FAIRS experiment on how the spectral density of breaking crest length changed as the wind sea aged (Gemmrich, 2005). Our model simulations, run in a partially-coupled mode, also examined carefully the complex relationship between the wind input and dissipation rate source terms. Special attention was also given to the ‘holistic’ issue of matching wind input to the *total* dissipation rate in the wave boundary layer.

During FY07, we turned our attention to the fully-coupled problem. To optimize our coupling strategy, we needed to develop a suitable spectral wind input formulation based on forcing a given spectral component by the wind speed at a height of a fixed fraction of its wavelength. This departs appreciably from the usual formulation based on the friction velocity u_* or a fixed wind speed, such as U_{10} .

WORK COMPLETED

During FY07 we continued our main effort on hurricane wind-wave model development, with explicit computation of wave breaking properties. Our capability for computing the directional wave spectrum was refined further, with particular emphasis on coupling the wave model to the overlying wind profile. This refinement was pursued while maintaining our goal of ensuring that our model could reproduce the observed evolution of integral wave properties, wind stress and breaking wave statistics at the spectral peak, where the relationship between the breaker properties and wave dissipation rate is known most reliably.

For this effort, our model development focused on the wind speed regime of $U_{10} \sim 12$ m/s which prevailed during the FAIRS experiment for which detailed information on the wind and wave fields was gathered, including breaking wave properties. We also sought to ensure that our coupled model was operational out to hurricane (~ 50 m/s) wind speeds, where the challenge was to achieve stable model behavior. We await breaking wave data from other CBLAST PIs to validate those very high wind speed results.

In our model-data comparisons, we examined a range of diagnostic properties: evolution of energy and spectral peak frequency, 1D transect wave spectra and spectral directional spreading. For the breaking data, we investigated breaking crest length spectra $\Lambda(c)$ (eg. Phillips, 1985), and used the observations of Phillips et al (2001), Melville and Matusov (2002) and Gemmrich (2005). For the directional spreading data, Hwang et al. (2000) provided the basis for our validation.

A state-of-the-art version of the ‘exact’ nonlinear source term S_{nl} (D. Resio, private communication) was used throughout this study to avoid known difficulties with approximate forms used in operational wave forecast models.

For the wind input source term $S_{in}(\mathbf{k})$, we built on our previous investigation described in our FY06 CBLAST Annual Report. Commonly implemented spectral wind input source terms S_{in} were seen to differ appreciably in their different weighting across the spectrum. These differences are seen in the S_{in} forms proposed by Janssen (1991), and Hsiao and Shemdin (1987). Figure 1 shows the dimensionless growth rate projected in the wind direction. There are very significant differences between these two forms, especially for low U_{10}/c (long waves). Also, they both appear to significantly overestimate the wind input growth rate at shorter scales, as evident in elevated levels of the computed wind stress. Invoking sheltering hypotheses is useful in alleviating this in the modeling.

Our proposed form for S_{in} implemented in the fully-coupled calculations follows the scale-dependent behaviour proposed by Donelan: the appropriate driving wind parameter for a given wave component is the wind velocity at an elevation of a fixed fraction of the wavelength of that component. We investigated a form of $S_{in}(\mathbf{k})$ based on $U(\lambda/n)$, assuming a form for the dimensionless growth rate proportional to $[U(\lambda/n)\cos\theta/c - 1]^\alpha$, where n is an integer, α is a real exponent and θ is the angle between the wave component and the mean wind. For the results shown below, we used $n=5$ and $\alpha=1.25$, with low sensitivity to the choice of α in the range 1 to 1.5. The growth rate magnitudes given by a tail-modified Janssen (1991) spectral growth form were adopted as a plausible reference (see Banner and Morison, 2006). This choice has strong implications for successfully modeling breaking properties at the spectral peak for evolving wind seas. The growth rate data trend of Snyder et al. (1981) for the dominant ocean waves (low U_{10}/c) is indicated in this figure for reference. The

wavelength dependent form for the growth rate proposed above is seen to provide a close replication of that data.

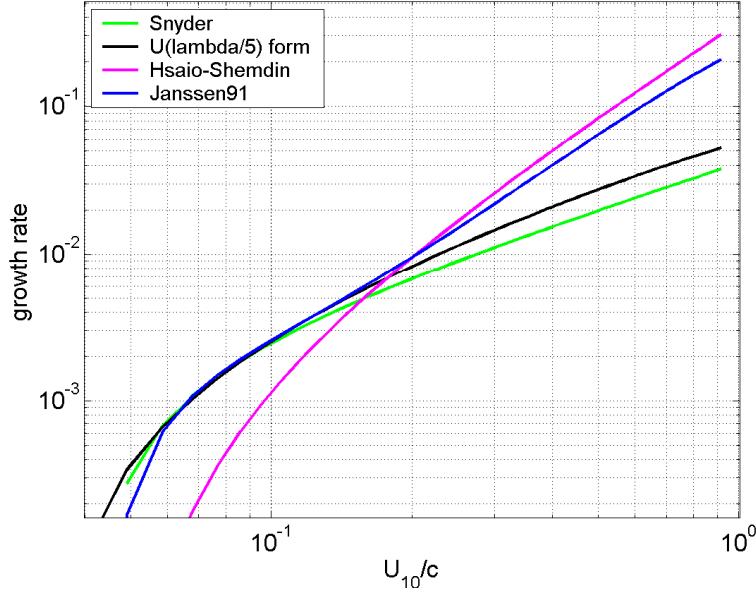


Figure 1. This logarithmic plot highlights the differences for developing seas ($U_{10}/c_p \sim 1.085$) between various non-dimensional spectral growth rate parameterizations used to force wind-wave forecast models. Note the observed growth rates for the dominant sea waves ($U_{10}/c \sim 1$) differ appreciably. The wavelength dependent form we investigated is seen to fit the preferred Janssen91 growth rates for the dominant waves, with a reduced input to the shorter waves (higher values of U_{10}/c).

Our spectral wave energy dissipation rate source term, S_{ds} , has a primary dependence on wave nonlinearity through its functional dependences on the spectral saturation (see AB02).

$$S_{ds}(k, \theta) = C [(\tilde{\sigma} - \tilde{\sigma}_T) / \tilde{\sigma}_T]^a \tilde{\sigma}^b + \varepsilon_{res}] (\sigma / \sigma_m)^c \omega F(k, \theta) \quad (1)$$

Here σ and $\tilde{\sigma}$ are respectively the saturation and saturation normalized by the directional spreading width, $\tilde{\sigma}_T$ is threshold normalized saturation and σ_m is the saturation at k_m , the mean wavenumber at the transition from the peak enhancement region to the spectral tail. The breaking threshold switching exponent a was taken as 2, with b taken as 2 and c taken as 4, based on matching to the high wave number form of $S_{in}(k)$. The tuning constant C was chosen to provide the optimal match to observed duration evolution data of the spectral peak energy and peak frequency (eg. Young, 1999). ε_{res} is a small background residual dissipation coefficient that is consistent with observed decay rates of swell leaving storm areas.

The model performance was investigated by extensive computations of the evolution of the directional wave spectrum using the above source terms in the standard radiative transfer equation. We studied duration-limited evolution, over a wide bandwidth typically out to several Hz. As shown below, the model performed very well in reproducing a broad range of observational spectral properties.

With these diagnostic benchmarks satisfied, we proceeded to make extensive calculations of the spectral density of breaking crest length per unit area, and how these breaking wave spectra change with wind speed and wave age. It should be noted that the model computes the evolution of the spectral dissipation rate S_{ds} , and the precise link between S_{ds} and the spectral density of breaking crest length/unit area $\Lambda(c)$ is not well understood, and is a current research topic of considerable complexity. The assumption that wave breaking dissipation is localized spectrally is not well established, i.e. that spectral dissipation at scale c (or k) is only associated with breaking waves of that scale. It is most likely to be valid for the dominant (spectral peak) waves. Phillips (1985) proposed that if *localized* spectral dissipation is assumed, then $\Lambda(c)$ may be calculated from:

$$S_{ds}(c) = b (c^5 / g) \Lambda(c) \quad (2)$$

The non-dimensional coefficient b reflects the strength of breaking, but its value, as well as its spectral dependence, cannot be derived from theory and needs to be assessed observationally. We used the unique results of Gemmrich (2006) who measured both the total dissipation rate S_{ds} and $\Lambda(c)$ in the field, for which $b \sim 2.5 \times 10^{-5}$ was reported. We investigated whether our S_{ds} model provides a self-consistent and robust formulation for his observations under the localized spectral dissipation assumption (2). This is expected to be most applicable for the waves in the spectral peak region. Thus our primary goal was to determine whether (2) could reconcile observed and computed breaking crest length spectral density levels for the dominant waves. Progress on this key aspect is described below.

For the shorter waves above the spectral peak, there are also *non-local* sources of dissipation, such as attenuation of short waves both by longer breaking waves and also through strong nonlinear interaction with non-breaking, steep longer waves. In strongly forced sea states (typical of hurricanes), these spectrally non-local effects are likely to be significant. We have already begun work on modeling these effects, which presents considerable challenge, and will seek to refine this during FY07.

RESULTS

Refinement of fully coupled computational results – reconciliation with FAIRS Experiment wind, wave height and breaking wave data

The breaking wave data used for our validation was gathered during the FAIRS experiment and reported in preliminary form by Gemmrich (2005). There were synchronous measurements of wind speed and direction, wind stress and wave height during the observational period. However, a unique feature of this data set was the measurement of wave breaking properties for a developing wind sea ($U_{10}/c_p \sim 1.1-1.2$), in addition to those for mature sea conditions. Such data for growing wind seas was not previously available. The crucial feature evident for the developing seas is the significant breaking occurring at the *spectral peak* wave scales, even though the wind input is relatively weak. This presented a very significant challenge for the model to reproduce.

The results for integral wave spectral properties, mean energy and peak frequency, achieved a very close correspondence with observed evolution behavior in Young (1999), as seen in Figure 2 below. We also obtained very close model agreement, both level and spectral slope, with the high wavenumber tail of the 1-D transect spectrum observed by Melville and Matusov, 2002 (Figure 3). Modeled directional spreading properties compared very favorably with the data of Hwang et al. (2000) (Figure 4) and also with high wind speed results from the recent GOTEX experiment (Melville

et al, 2005), in regard to both the bimodal shape at higher wavenumbers and the mean spreading width against wavenumber. Computed wind stress levels closely matched observational levels (Figure 5).

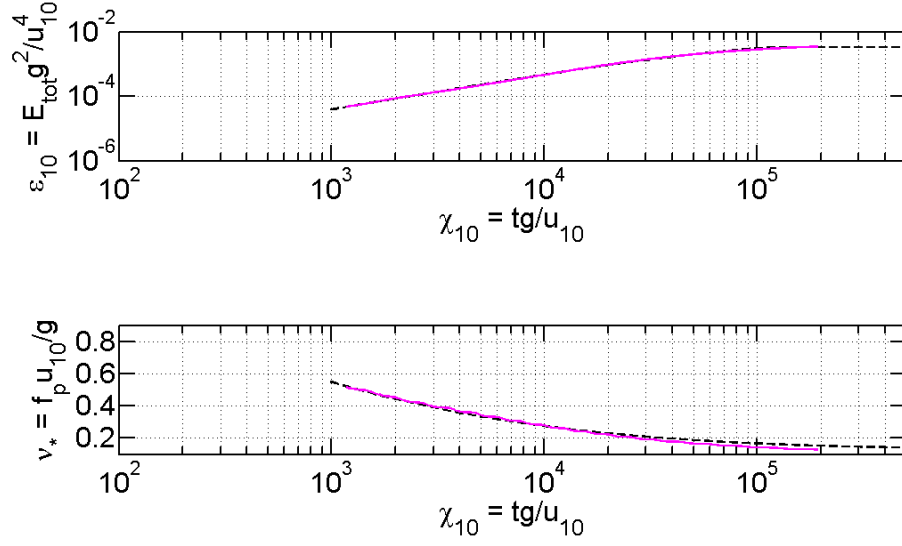


Figure 2. Evolution of the non-dimensional wave energy (upper panel) and non-dimensional dominant wave frequency (lower panel) against non-dimensional time, generated from the fully coupled model. The dashed curve is the trend of available field observations (Young (1999)).

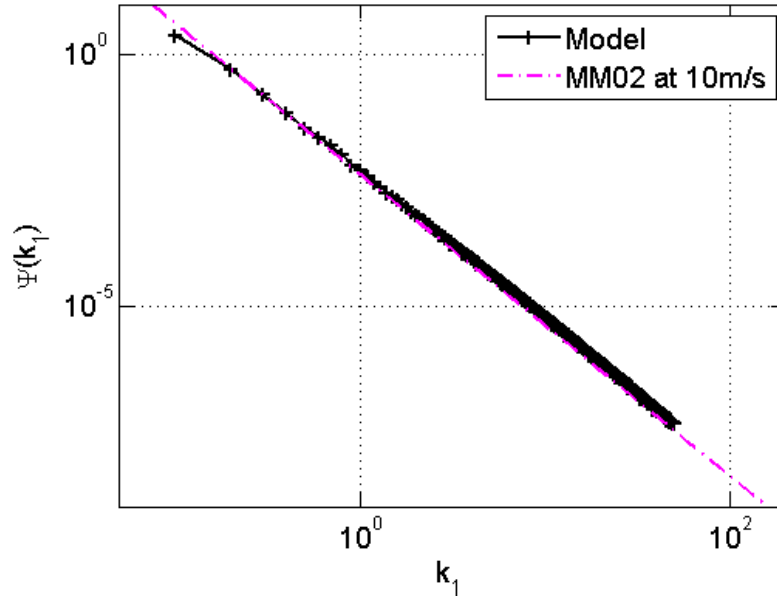


Figure 3. Computed one-dimensional transect spectrum in the dominant wave (k_1) direction for mature seas, showing a k_1^{-3} behavior. The background curve was measured during mature wind seas in 7-13 m/s wind speeds off the US east coast by Melville & Matusov (2002), designated as MM02.

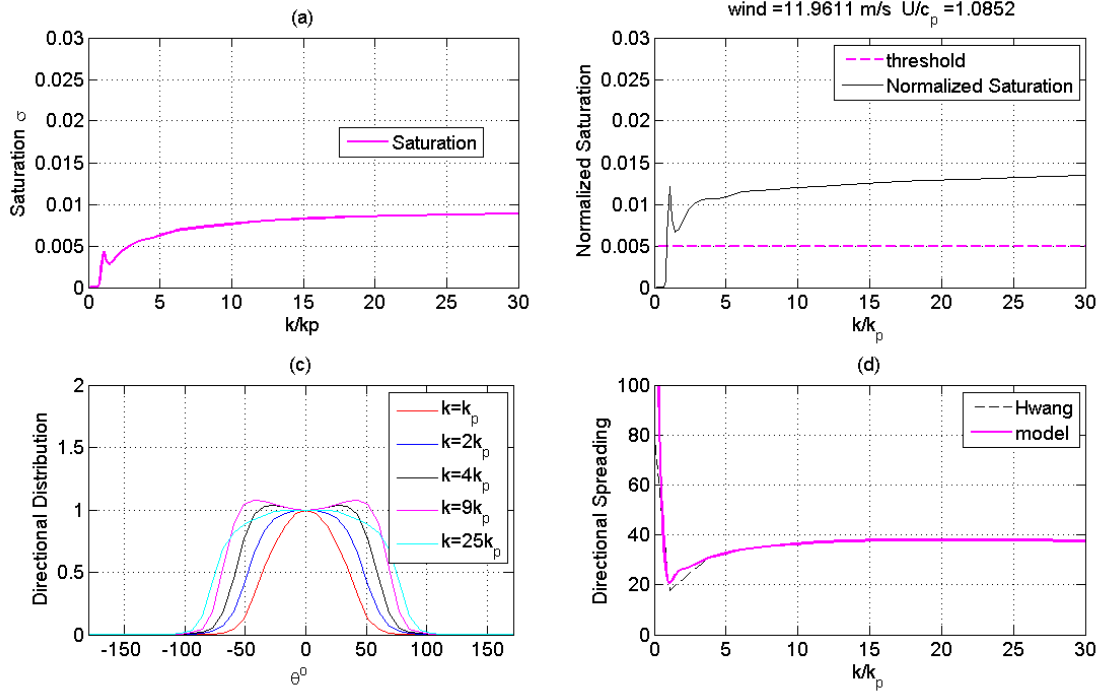


Figure 4. (a) azimuth-integrated spectral saturation against distance from the spectral peak wavenumber, for inverse wave age $U_{10}/c_p \sim 1.085$ (b) corresponding normalized saturation formed from (a) by division by the mean spreading width in radians (c) directional distribution of energy at different wavenumbers relative to the spectral peak. These agree with the observations reported in Fig. 2 of Melville et al (2005) (d) variation with wavenumber of the mean spreading width in degrees, compared with observations reported by Hwang et al. (2000). The calculations match the observed peaked off-wind nature and strong broadening of the direction spreading towards the shorter wave scales reported in recent field studies.

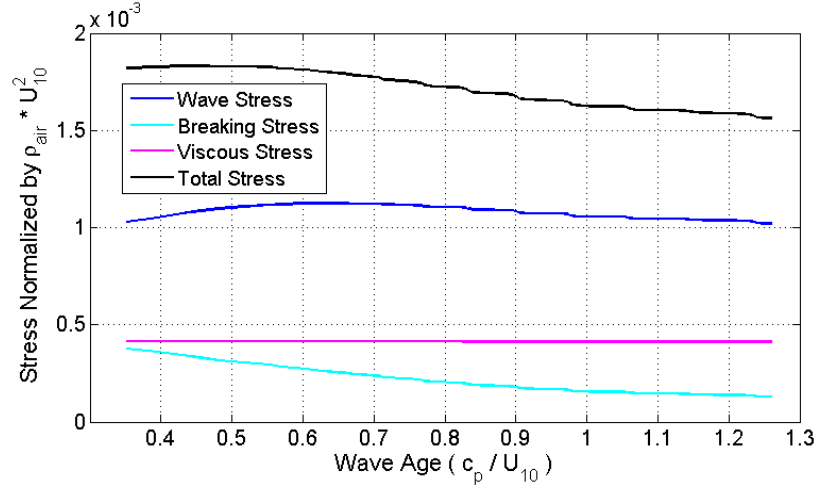


Figure 5. Evolution with wave age of the normalized total wind stress (the sea surface drag coefficient). The fully developed sea asymptotic value is close to the observed level of 0.0015. The behavior of the normalized wave stress, breaking stress and viscous tangential stress components is shown the wind sea ages. The viscous stress follows the estimate by Banner and Peirson (1998).

Figures 6 and 7 show the modeled and observed spectral distributions of $\Lambda(c)$ for different wave ages. The behaviour at the spectral peaks of the developing seas (period 1 where $c_{peak} \sim 10$ m/s) and mature seas (period 3 where $c_{peak} \sim 13$ m/s). These are the focus of the breaking forecasting validation.

A comparison of these observed and model results shows that the spectral peak level of $\Lambda(c)$ changes over an order of magnitude as the wave age changes from developing seas to mature seas. For the dominant waves, the results indicate very encouraging agreement between observed and forecast levels during both of these observational periods. Further comparisons with data are now needed to establish the robustness of the modeling approach used here. For the shorter waves, we note that model predictions are not in accord with the data, as foreshadowed above, and will be the investigated further.

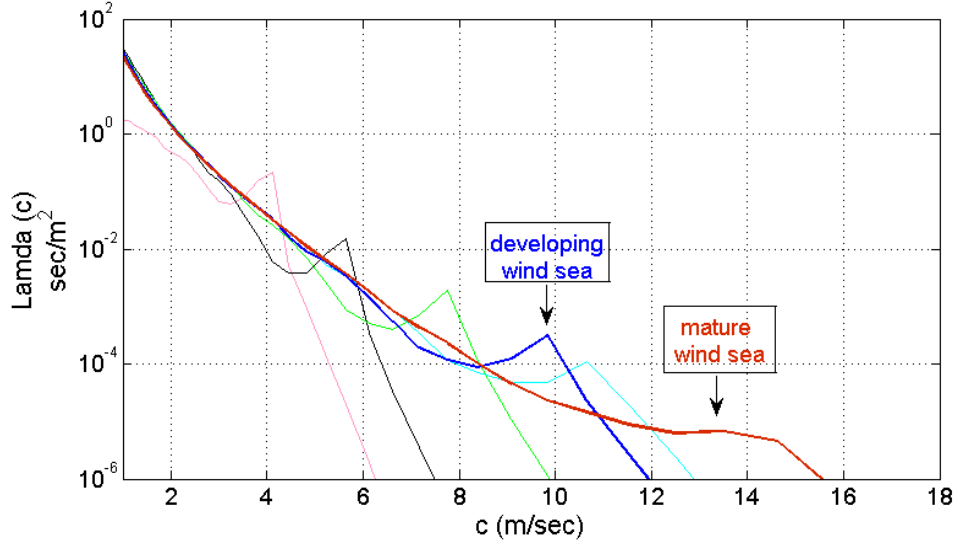


Figure 6. Computed evolution of the normalized spectral density of breaking crest length/unit area (Λ) against the wave speed c at different stages of wave development. The results for the developing wind seas and mature seas are indicated, and may be compared with Figure 7. The enhanced Λ level observed at the evolving spectral peak tends to disappear towards full development.

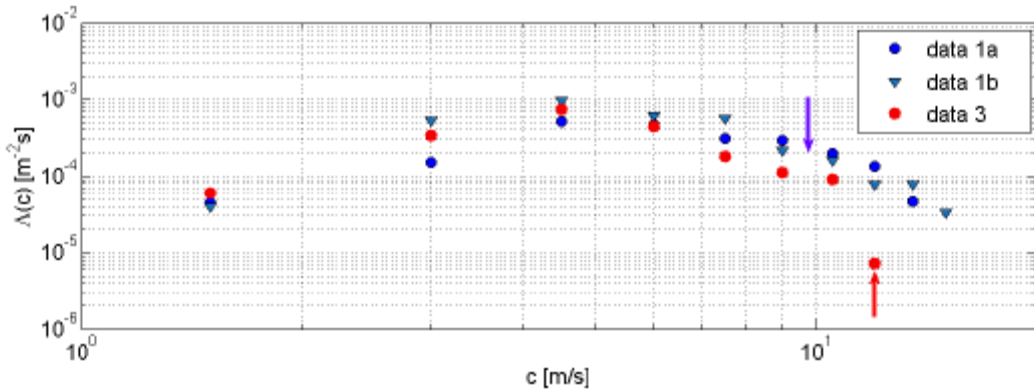


Figure 7. Measured breaking wave crest length spectral density $\Lambda(c)$ for developing seas (blue circles and triangles) and mature seas (red circles) during the evolution for $U_{10} = 12$ m/sec (Gemmrich, 2005). The red and blue arrows indicate the spectral peaks corresponding to the wave age conditions when the spectral peak wave speeds were 10 m/sec and 13 m/sec respectively.

Overall, these fully-coupled model results for forecasting 12 m/s wind speed wave spectra, including dominant wave breaking properties, are very encouraging. This will be described in greater detail in a manuscript currently in preparation (Banner and Morison, 2007).

This fully coupled model has also been tested recently at wind speeds of 45 m/s, for which hurricane wave data was available from Walsh (private communication). There was no re-tuning of any of the

coefficients in moving from 12/m/s to 45m/s and the model was found to run very stably. The results tracked closely the dimensionless energy versus duration curve, while the dimensionless wave frequency decreased at a slightly faster rate than the standard curve (shown in the lower panel of Figure 2). The wind stress initially rises, peaks and then decays as the wind sea ages. The computed drag coefficient was comparable with levels reported for hurricane wind stress observations (e.g. Powell et al (2003)). We are investigating whether our model physics can reproduce the observed attenuation of C_d with increasing wind speed above 33 m/s, which is as yet unexplained.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking and spray/droplet production rates, will provide more reliable parameterizations of these processes and closely related air-sea fluxes when introduced into operational forecast models. These improved parameterizations will increase the reliability of operational sea state and marine meteorological forecasts, especially during severe marine weather conditions. Of particular benefit will be the capability to provide routine forecasts of occurrence rate of dangerous breaking waves.

RELATED PROJECTS

The recently concluded ONR 322PO project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) investigated the influence of steep waves and wave breaking on the wind input source function in strongly forced, constant depth, shallow water environments. This data set has been analyzed and a set of papers on the methodology and results has appeared in refereed journals [e.g. Donelan et al, 2004; Babanin et al., 2005].

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